Honeywell (formerly AlliedSignal, Inc.)

PIM Process Used to Manufacture Ceramic Components

Manufacturers continually seek to develop more resilient and cost-effective materials to use in their products. Ceramics have specific characteristics that make them a plausible replacement for several materials, including steel. Ceramics products are lighter, less corrosive, more resilient in high-temperature environments, and sustainable in nonlubricated environments. In 1991, plastic powder injection molding (PIM) production in the United States was a $20 billion industry. In contrast, the use of PIM in the ceramics industry was relatively small at $10 million annually. Honeywell (formerly AlliedSignal, Inc.), however, believed that an entire ceramics-based parts industry could be created, based on the existing PIM process for plastics, and had the potential to grow into a $1 billion market within 10 years.

Therefore, in 1993, Honeywell proposed to the Advanced Technology Program (ATP) a three-year project to develop a cost-effective ceramic PIM process. Honeywell, which pioneered this technology, needed ATP funding because of the high technical risk of the work. Upon completion of the project in 1997, Honeywell had realized measurable results in several areas, including feedstock production and component manufacturing for a few small parts. The new process has proved most effective in minimizing machining for high-volume, labor-intensive parts.

Over time, commercialization based on this project's technical success is being realized in several sectors far beyond the original scope of this project: ceramic chinaware, spark plugs, oxygen sensors, ball bearings, manufacturing components, engine components, and bio ceramics. Honeywell also used the knowledge gained to expand its product development into metal PIM. This ATP-funded project helped to catapult the small ceramic PIM industry from approximately $10 million annually to one that in 2002 was estimated to exceed $160 million, with almost 10 percent annual growth.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
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Research and data for Status Report 93-01-0104 were collected during October - December 2001 and April - May 2003.

PIM Process Could Lower Cost of Ceramics Production

Ceramics have the potential to replace materials such as steel in many applications because they are lighter, less corrosive, more heat-resistant, and sustainable in nonlubricated environments. Moreover, ceramics are less likely to be rejected by the human body than other materials. Over the last several decades, scientific improvements have led to fundamental material technology advances that have made it possible to use ceramics in a wide variety of automotive, consumer, industrial, aerospace, military, and medical products. Although the adoption of ceramic-based products had increased by 1993, manufacturers in several industries had experienced difficulty finding a means to cost-effectively produce these components. Honeywell (formerly AlliedSignal, Inc.) believed that by applying powder injection molding (PIM), the process used successfully by the plastics industry, to ceramics production, they could create a responsive, low-cost, high-volume manufacturing base for shaping ceramic materials into engine components and could quickly build an entire ceramics-based parts industry. They projected that, if successful, the ceramics PIM industry could grow from its existing annual market base of $10 million to $1 billion in 10 years. However, due to the project's potential for failure, Honeywell was hesitant to fund the project and needed to find a way to attract outside collaborators. Therefore, Honeywell applied for funding from ATP and, in 1994, received a three-year award of approximately $1.6 million to develop ceramic PIM technology.

Collaboration Provides Framework for Success

To attain their objective of developing a cost-effective ceramic PIM process, Honeywell and its subcontractors (Pennsylvania State University; Cincinnati Milacron; Autolite, a subsidiary of Honeywell; Golden Technologies; and Honeywell Aerospace), needed to achieve these specific milestones and results:

> ***Milestone:*** Develop cost-effective ceramic feedstock formulations (alumina and silicon nitride), which possess rheological (dealing with the deformation and flow of matter) and molding characteristics similar to those of plastic feedstock. ***Result:*** Selected and characterized raw materials and formulations.
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> ***Milestone:*** Develop a predictable shrinkage control process for finished products. ***Result:*** Identified key molding variables, conducted molding trials, and attained reproducible size and improved shrinkage tolerance to produce near-net-shape ceramic components; incorporated gel strength-enhancing additives to improve the stiffness of molded parts and developed new alloys for molding machine components to minimize rust contamination; defined the relationships between gel strength, blend formulation, time, and temperature stability.
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> ***Milestone:*** Develop a safe binder-removal process. ***Result:*** Carefully configured dies to release water and minimize blister formation.
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> ***Milestone:*** Achieve aging and molding characteristics for ceramic PIM that are similar to those characteristics in plastic PIM. ***Result:*** Injection molding gives better component density than slip casting; achieved molding machine process controls to create high-quality alumina and silicon nitride compounds; developed best practices for designing molds using water-based ceramic PIM.
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> ***Milestone:*** Incorporate plastic PIM equipment into the ceramic PIM process by making only minor modifications. ***Result:*** With slight modifications, used plastic PIM machines to complete preliminary high-precision prototype molding of both alumina and silicon nitride ceramic compounds at Autolite, Golden Technologies, and Ceramic Components; completed preliminary prototypes for two additional customers, demonstrated the process, and determined production rates for a wide variety of specialty electrical parts.

The project team that Honeywell selected to accomplish these tasks included the following members:

- **Pennsylvania State University**, which has an established center for materials research with a technology base in rheological and tribological science (dealing with the design, friction, wear, and lubrication of interacting surfaces in relative motion, as in bearings or gears)
- **Cincinnati Milacron**, which is the largest U.S. manufacturer of injection molding equipment
- **Autolite**, which is the largest U.S. manufacturer of alumina spark plugs
- **Golden Technologies**, which is a major manufacturer of alumina ceramic products
- **Honeywell Aerospace**, which was developing a manufacturing base for advanced silicon nitride ceramics

Ceramics have the potential to replace materials such as steel in many applications.

Throughout the project, each team member played an integral role in developing feedstock and manufacturing prototype components. Several team members, including Autolite, Honeywell Aerospace, and Honeywell's in-house research team, regularly developed various feedstock formulations. As these formulas were developed, Golden Technologies and Pennsylvania State University conducted molding trials and studies, which measured the materials' rheological characteristics, heat capacity, thermal conductivity, and other properties important for conducting mold-fill modeling. Test and trial results revealed inefficiencies that were quickly corrected, and eventually the team members obtained the desired characteristics. Reaching this milestone made PIM machine testing with alumina and silicon nitride feedstock formulations possible. With slight modifications, the plastic PIM machines were used to produce several small ceramic components.

Technical Accomplishments Encourage Feasibility of Broad-Based Production

Although the project team consistently achieved and improved upon the prototype production of small products and components, they aspired to develop methods and processes to enable the production of large components and products. In early 1997, near the project's completion, molding trials at Bemis Manufacturing Company successfully fabricated large-size ceramic components by using plastic molding machines. The trials supported the notion that plastic molding equipment could also be utilized in ceramic PIM and provided encouragement to other plastic molders to expand their product lines and benefit from the use of preformulated feedstock.

Superior Feedstock Formulations Reduce Costs

Honeywell and its team members developed several ceramic feedstock formulations for use in PIM equipment. The new feedstock formulations, composed of silicon nitride and alumina, retained superior molding, shrinkage, and pressure characteristics that have been successful in reducing development costs for several products in various industries. These include mechanical applications (e.g., seals, nozzles, spark plugs, and sensors), manufacturing applications (e.g., stamping punches and guide rollers), and even bio-ceramics (e.g., artificial bones for humans). Honeywell and its partners sold feedstock to plastic PIM manufacturers that had switched to or had incorporated ceramic PIM into their manufacturing processes. However, the volume and profit margins were too low, and the project team ultimately discontinued this practice.

Manufacturers in several industries had experienced difficulty finding a means to cost-effectively produce these components.

Approximately 40 to 50 manufacturers have adopted these new processes. Those that are using the new preformulated feedstock formulations include Saint Gobain Advanced Ceramics (formerly Carborundum), Coors Ceramics, Norton Ceramics, Kyocera Inc., and NTK Ceramics. The superior feedstock compositions used by these manufacturers have enabled the development of various products that now provide more heat-resistant, longer lasting parts to consumers. This ATP-funded project brought credibility to the process, and several other companies have developed their own formulas. Depending on the geometry of a part, it may be produced by slipcasting, gel casting, die pressing, or PIM. The PIM process is cost effective for high-volume parts with complicated shapes.

Analyses Prove Ceramic PIM's Viability

After the Honeywell team overcame several obstacles and reached many of its milestones, they completed four marketing and business case analyses on ceramic PIM. They conducted the analyses for specific products believed to have significant industry-wide impacts and large and immediate return-on-investment. These products included oxygen sensors, 8.5-mm spark plugs, and entire spark plug facilities. The results of the analyses on the products and manufacturing facilities proved to be invaluable. The four marketing and business case analyses are summarized below:

- Analyzed a retrofit of Honeywell’s Fostoria spark plug facility to accommodate the use of injection molding. Comparing conventional 8.5-mm spark plugs to PIM spark plugs revealed that conventional spark plugs cost more than those developed by the PIM processes; therefore, the plant was partially retrofitted. The plant began producing racecar spark plugs made with insulators that had been injection molded.

- Assessed developing oxygen sensor thimbles for oxygen sensors using injection-molding methods. The analysis revealed that significant cost savings could be realized if injection molding was adopted. In 1998, one million oxygen sensor thimbles were produced per year using a traditional zirconia material system. The analysis predicted that manufacturers would be able to increase production to 1.147 million thimbles per year using the injection-molding process. Furthermore, a materials savings of 33 percent and a scrap savings of 80 percent could be gained, for a 14.7-percent reduction in fixed costs.

- Evaluated insulators for three types of oxygen sensors. The analyses determined that a 30-percent savings for the three insulators would exceed $300,000 per year.

- Predicted that the manufacturing cost of bone china dinnerware with complex shapes, such as teacups, could be reduced by 10 to 40 percent.

Ceramic PIM Finds Widespread Acceptance

By 1996, acceptance of ceramic PIM within the industry was rapidly increasing. In fact, in June 1996, beta site testing of alumina formulations at five different ceramic fabricators validated strong commercial possibilities. This bolstered the confidence of several industries, such as consumer goods and automotive, to incorporate this technology into new and existing products, such as housewares and automobile gears.

Throughout the project, chinaware makers had displayed an interest in the development of ceramic PIM. In 1996, Honeywell demonstrated the ability to produce injection-molded bone china ceramic formulations in the shape of teacups that have a one-step, integrally molded handle and foot. The company indicated that this new process would provide a 10- to 40-percent cost reduction in dinnerware products that have complex shapes. Since that time, several companies have adopted the technology, including Lenox China in the United States, Wedgewood China in England, and Villeroy & Boch in Germany.

Continuing Impact of the Molding Techniques

Since the ATP-funded project ended in 1997, the company (now as Honeywell) has continued to produce ceramic PIM automotive parts (e.g., spark plugs and oxygen sensors) and aerospace parts for gas turbine engines (e.g., nozzles, seals, and shafts). They have patented and licensed this technology to other firms, which has led to significant growth in the industry ($160 million in 2001). This project brought credibility to the ceramic PIM process, which is now the method of choice when a company produces complex, high-volume ceramic components. Approximately 40 to 50 companies currently use the technology, and, of those, about 6 use the formula developed in this project. In addition, the ceramic PIM process is used to produce ball bearings, manufacturing components (e.g., stamping punches and guide rollers), and bio ceramics (e.g., artificial bones for human replacement surgery). Furthermore, Honeywell, in collaboration with Rutgers University, used this process to develop metal PIM, which led to the growth of a start-up company, Latitude Manufacturing Technologies.

In 1998, Honeywell produced and sold more than 800,000 oxygen sensors that contain injection-molded ceramic parts (insulators and thimbles). As predicted in the four marketing and business case analyses that Honeywell conducted, the company reduced its production costs by 30 percent, which resulted in a savings of $300,000.

Conclusion

This pioneering ATP-funded project proved the viability of applying powder injection molding (PIM) from the plastics industry to the ceramics industry. Furthermore, the process is now used in a wide variety of practical applications in the automotive, aerospace, manufacturing, and medical industries. The spillover resulting from this technology has initiated significant growth in the ceramic PIM industry, from $10 million in 1994 to $160 million in 2002, and has led to the use of the process with metal. This new industry is growing at a steady pace because of the increasing benefits of reduced manufacturing costs and increased parts life available to original equipment manufacturers and consumers.

PROJECT HIGHLIGHTS
Honeywell (formerly AlliedSignal, Inc.)

Project Title: PIM Process Used to Manufacture Ceramic Components (Ceramic Technology for Broad Based Manufacturing)

Project: To develop and test a user-friendly technology base for net-shape injection molding of complex ceramic parts using water-based injection molding systems for alumina and silicon nitride.

Duration: 04/01/1994-03/31/1997
ATP Number: 93-01-0104

Funding (in thousands):

ATP Final Cost	$1,600	50%
Participant Final Cost	1,596	50%
Total	$3,196	

Accomplishments: Honeywell (formerly AlliedSignal, Inc.) and its team members developed several feedstock formulations for use in ceramic powder injection molding (PIM) equipment. The new feedstock formulations, composed of silicon nitride and alumina, retain superior molding, shrinkage, and pressure characteristics. Consequently, the new feedstock has reduced development costs for several products in various industrial sectors, including chinaware, spark plugs, and oxygen sensor components.

One patent was approved as a result of this project, which formed the basis for additional patent applications following project completion:

- "Gel strength enhancing additives for agaroid-based injection molding compositions" (No. 5,746,957: filed February 5, 1997, granted May 5, 1998)

In addition, Honeywell has presented and published results from the ATP-funded project to increase the industry's knowledge of this technology. These presentations and publications include:

- Fanelli, A., and C. P. Ballard. "Advances in Water-based Powder Injection Molding." 1995 International Powder Injection Molding Symposium. State College, PA: July 19-21, 1995.
- Ballard, C. P. "Water-Based Ceramic Injection Molding Compounds." Society of Manufacturing Engineers. Detroit, MI: March 27-29, 1996.
- Ballard, C. P. "Ceramic Injection Molding Meets the Demand for Manufacturing Complex Shapes." Ceramic Industry. March 1997.
- Ballard, C. P. "Targeting Ceramic Technology for Business Growth." The Gorham Advanced Materials Conference on Advanced Ceramics for the New Millennium. Atlanta, GA: March 10-12, 1998.· Ballard, C. P., and M. Zedalis. "Advances in Powder Injection Molding." ANTEC'98, Society of Plastic Engineers. Atlanta, GA: April 26-30, 1998.
- Ballard, C. P. "Advances in Ceramic Powder Injection Molding." PIM 98 Powder Injection Molding: An Advanced Manufacturing Technology. University Park, PA: April 27-29, 1998.

Commercialization Status: Since the completion of this project, ceramic PIM technology has been incorporated into a range of products that far exceeds the expectations of the project team. Applications include chinaware, spark plugs, oxygen sensors, ball bearings, manufacturing components (e.g., stamping punches and guide rollers), engine and machine components (e.g., nozzles, seals, shafts, valves, and heating units), and bio ceramics (e.g., artificial bones for human replacement surgery). Moreover, several additional companies have developed products and/or feedstock using the processes and technology resulting from this ATP-funded project. These companies include Norton Ceramics, Morgan Crucible, Vesuvius Group, A. P. Green Industries, Baker Refractories, National Refractories, and Saint Gobain (formerly Carborundum).

Component and product development is increasing steadily. This project helped to catapult the small ceramic PIM industry from approximately $10 million annually in 1994 to one that, in 2002, was estimated to exceed $160 million. This represents an annual growth rate of almost 10 percent. In addition, the ceramic PIM process spawned a spin-off technology, manufacturing metal components using metal PIM.

Outlook: The ceramic PIM industry is growing steadily as competition increases. The outlook for the ceramic PIM industry and for Honeywell's ceramic PIM process is excellent.

Composite Performance Score: * *

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Subcontractors:

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- Golden Technologies
- Honeywell Aerospace